Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2016

Thermal-hydraulic Analysis of High-temperature Cover Gas Region in STELLA-2

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1. Introduction

Based on the long-term nuclear program plan approved by Korean government, development of PGSFR (Prototype Generation-IV Sodium-cooled Fast Reactor) has been underway [1]. To support this, a large-scale sodium thermal-hydraulic test program called STELLA (Sodium Test Loop for Safety Simulation and Assessment) also has been in progress since 2009 [2]. The first phase of the program was focused on the key sodium component tests, and the second one has been concentrated on the sodium thermal-hydraulic integral effect test (STELLA-2). Based on its platform, simulation of the PGSFR transient will be made to evaluate plant dynamic behaviors as well as to demonstrate decay heat removal performance. Therefore, most design features of PGSFR have been modeled in STELLA-2 as closely as possible [3].

The similarities of temperature and pressure between the model (STELLA-2) and the prototype (PGSFR) have been well preserved to reflect thermal-hydraulic behavior with natural convection as well as heat transfer between structure and sodium coolant inside the model reactor vessel (RV). For this reason, structural integrity of the entire test section should be confirmed as in the prototype. In particular, since the model reactor head in STELLA-2 supports key components and internal structures, its structural integrity exposed to high-temperature cover gas region should be confirmed.

In order to reduce thermal radiation heat transfer from the hot sodium pool during normal operation, a dedicated insulation layer has been installed at the downward surface of the model reactor head to prevent direct heat flux from the sodium free surface at 545^{o}C.

In this paper, the three-dimensional conjugate heat transfer characteristics for the full-shape geometry of the upper part of the model RV have been analyzed by using a CFD method. As a result, the steady-state temperature distributions from the cover gas region to the environment through the model reactor head have been obtained to evaluate the structural integrity of the model reactor head.

2. Methods and Results

2.1 General Descriptions of STELLA-2

STELLA-2 consists of eight independent sodium loops, which are 2 loops of the model IHTS, 2 loops of the model ADHRS, 2 loops of the model PDHRS, and 2 loops of PSLS. All sodium loop piping systems have radial symmetry around the main vessel, and the overall size of the whole scaled setup was estimated to be around 12 m by 15 m in occupied area and around 30 m in actual height [2][3]. General configuration of the model reactor vessel (RV) and reactor internals (RI) is identical to that of the prototype as depicted in Fig. 1.

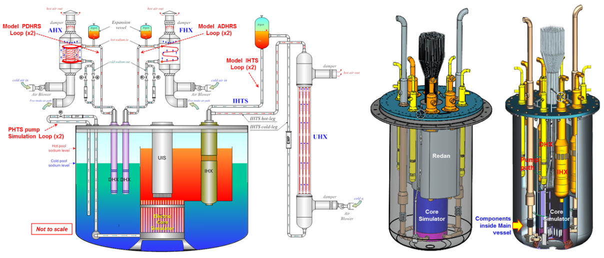

Fig. 1. STELLA-2 Schematic and solid modeling

2.2 Heat Transfer Analysis using a CFD Method

Analysis domain of the upper part of the model RV is shown in Fig. 2 with the specific boundary conditions. The domain covers the vertical region from hot sodium pool free surface to the upper insulation layer at the upward surface of the model reactor head.

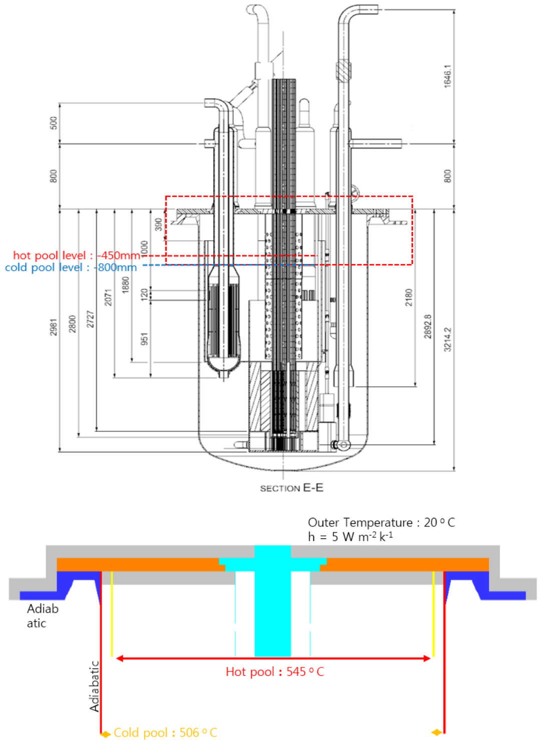

Fig. 2. Analysis domain and specific boundary conditions

In regard to the thermal boundary conditions, the temperature conditions interfacing the hot and cold sodium pool free surface were respectively set to be 545^{o}C and 506^{o}C based on the preliminary sodium pool analyses results [4]. Outer wall of the model RV was assumed to be adiabatic. Thermal conductivity of all insulation layers was set to be 0.07 W/m/K. The convection heat transfer coefficient to the environment defined at the exterior surface of the insulation layer on the model reactor head was set to be 5 W/m^2/K, and the ambient temperature was assumed at 20^{o}C at all cases.

Total three independent analysis cases have been considered in conjunction with the insulation type or methods for the model reactor head, which are (A) insulation layer thickness of 60 mm fully covering the entire upward surface of the head, (B) insulation layer thickness of 105 mm fully covering its entire upward surface, and (C) insulation layer thickness of 105 mm covering its upward surface only. For all cases, the dedicated insulation layer with the thickness of 60 mm is installed at the downward surface of the model reactor head inside the model RV. All analysis cases are graphically presented in Fig. 3.

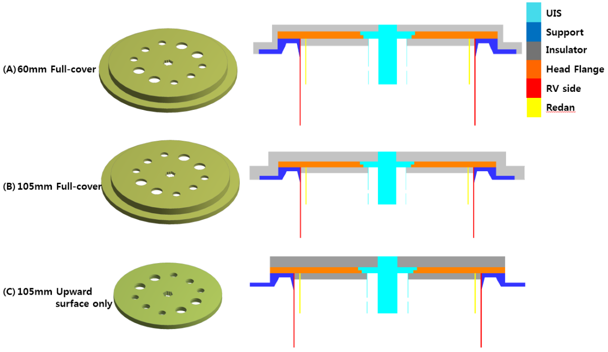

Fig. 3 Illustration of analysis cases for the model head

Natural convection in Argon cover gas region with conjugate heat transfer including thermal radiation was analyzed by using the commercial package of ANSYS V16.1 [5]. Discrete Transfer Model was implemented to solve thermal radiation heat transfer, and SST k-w model was also implemented for turbulent natural convection analysis. For all analysis cases, total approximately 2.3 million hybrid meshes (tetrahedron+ hexagonal) have been used. Fig. 4 shows the detailed mesh model of the entire analysis domain.

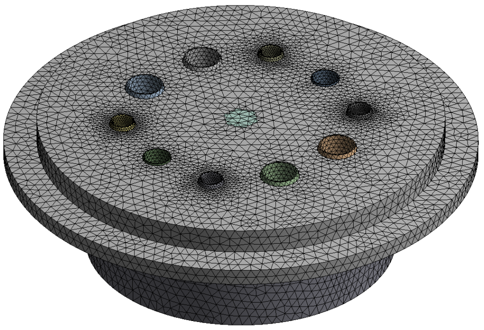

Fig. 4 Detailed Mesh Model (ISO view)

2.3 Results and Discussions

Figs. 5 and 6 graphically illustrate overall temperature distributions at different analysis cases. Fig. 5 shows the vertical temperature distributions of the insulation layers and the circular disk, respectively. If the exterior surface of the model reactor head is fully covered with insulation layer, the temperatures of both insulation layer and the model reactor head are distributed at higher value. On the other hand, if the exterior rim of the circular disk interfacing with the head support structure is open to the environment (Case-C), it was found that both temperatures are well maintained at relatively lower temperature.

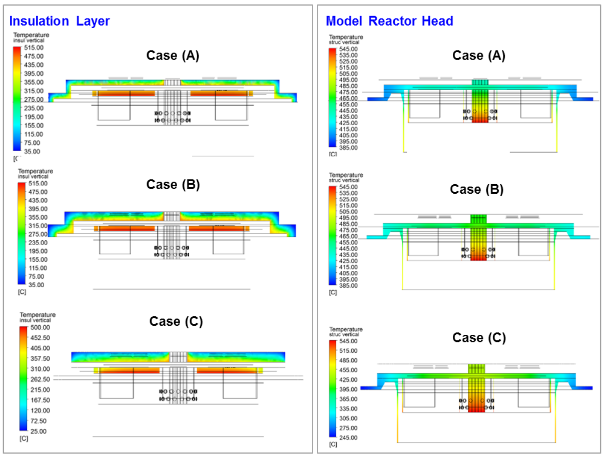

Fig. 5 Vertical Temperature distributions of insulation layer and circular disk

Since axial thermal conduction heat flow transferred from the hot sodium pool along the several components installed inside the model reactor vessel, higher temperature distributions over 350^{o}C were quantitatively obtained at around the penetration parts of the circular disk. In particular, it was also observed that the average temperature of the reactor head goes up as the insulation thickness becomes thicker and the covered area broadens. Based on the trend, it was confirmed that the average temperature of the case (C) -'for insulation layer thickness of 60 mm covering the upward surface only of the head'- was obtained at around 352^{o}C, which slightly exceeds the temperature design requirement of 350^{o}C.

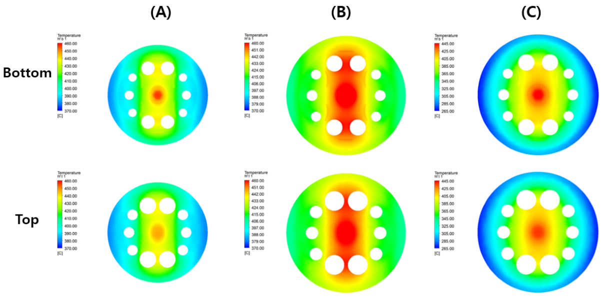

Fig. 6 Temperature distributions of the reactor head (Bottom & Top)

Figs. 7 and 8 show the temperature profiles along the different direction line that represent either the longest distance across the Redan structure (Line 1) or its shortest one (Line 2). As shown in both figures, it was well shown that the hot spots are evenly distributed at around the central part of the circular disk and the temperature of the case (C) rapidly decreases at the outer rim of the circular disk in both cases.

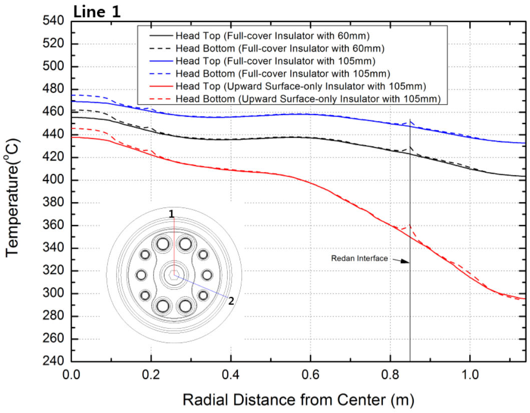

Fig.7 Radial temperature profiles on line 1

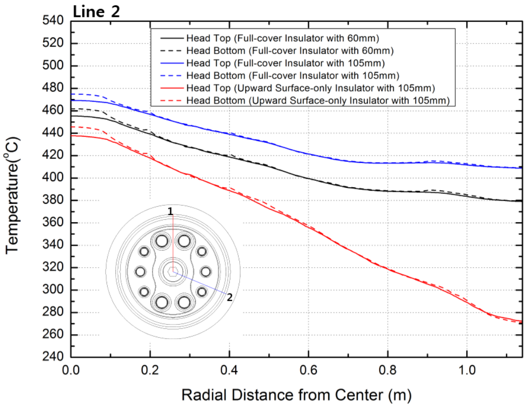

Fig.8 Radial temperature profiles on line 2

3. Conclusions

Three-dimensional conjugate heat transfer analyses for the full-shape geometry of the upper part of the model reactor vessel in STELLA-2 have been carried out. Based on the results, steady-state temperature distributions in the cover gas region and the model reactor head itself have been obtained and the design requirement in temperature of the model reactor head has been newly proposed to be 350°C. For any elevated temperature conditions in STELLA-2, it was confirmed that the model reactor head generally satisfied the requirement. The CFD database constructed from this study will be used to optimize geometric parameters such as thicknesses and/or types of the insulator. The structural integrity of the model reactor head will be assessed as well.

ACKNOWLEGEMENT

This work was supported by the National Research Foundation (NRF) Grant Funded by the Korea government (MSIP). (No. 2012M2A8A2025635)

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